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National
Engineering
Laboratory

Wave Energy Studies

at the

U.K. National Engineering Laboratory

For Rural and
Island Communities

by
George Elliot and
Graham Roxburgh

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WAVE ENERGY STUDIES AT THE
UK NATIONAL ENGINEERING LABORATORY

G Elliot* and G Roxburgh**

*National Engineering Laboratory, East Kilbride

**Roxburgh and Partners, Consulting Engineers, Glasgow

ABSTRACT

The work programme carried out into the development of the oscillating water column from the basic concept to a major power station design is described. The validity of a small wave-power station serving a remote community as a first objective in an overall development plan for wave energy is discussed.

KEYWORDS

Wave energy; oscillating water columns; Francis turbine; floating offshore structures; fixed offshore structure; design optimization.

INTRODUCTION

In 1974 the National Engineering Laboratory (NEL) undertook a study on behalf of the Department of Energy into the economic and technical feasibility of large-scale generation of electricity from the sea waves in UK offshore waters. The study showed that wave energy had been a source of interest for many years and listed some 340 UK patents dating back as far as 1856 for devices which were claimed to be able to utilize sea wave energy.

The 1974 study (Leishman and Scobie) covered many aspects of wave energy and examined the knowledge which was available regarding energy levels around the UK coasts, as well as the impact on the environment of capturing such energy. The report identified where active research into wave energy was being undertaken and showed that, up until 1973, it had been of little interest and a low key activity. However, during the course of the study, a tremendous surge of interest was taking place caused by the action of the OPEC countries in 1973 which greatly affected the world's oil supplies.

The greatest interest was being shown in both Japan and the UK where several universities and other organizations had commenced research into the harnessing of wave energy. NEL decided to participate in the development of wave energy devices. Because of their experience in offshore activities as well as their special facilities in turbo-machinery, the oscillating water column principle was selected as being the most appropriate to NEL's expertise. Although some work was being carried out in Japan the principle was not being studied or developed in the United Kingdom. NEL submitted a proposal to the Department of Energy to examine the oscillating water column. This was accepted and resulted in a programme of work funded by the Department of Energy.

EVOLUTION OF THE CONCEPT AND DESIGN

The initial investigations involved examining the simple inverted cylinder oscillating water column concept (Meir, 1978). Tank experiments on two-dimensional models demonstrated that, irrespective of depth of immersion, the capture efficiency of such a cylinder could never exceed 50 per cent. The energy in the incident wave was either transmitted and hence lost, or reflected back from the device. This was concluded to be the case with any arrangement of multi-directional symmetry.

In order to increase efficiency it was postulated that an asymmetric device in which the trailing edge of the column was extended downward would improve energy extraction by reducing or eliminating the transmitted wave energy (Fig. 1). This proved to be the case and very high peak efficiencies were achieved.

The further development of the concept was the introduction of a bottom reflector. This had the effect of improving the coupling between the incident wave and the water column which, as well as maintaining the high peak efficiencies, had the effect of broadening the band idth of the response of the device (Fig. 2). This of course is a desirable feature because the incident wave energy contained in the sea is made up of a fairly wide bandwidth of individual wave frequencies. This asymmetrical column with bottom reflector was the subject of a substantial amount of experimental and theoretical work in order to optimize and understand the features of a column of this shape (Fig. 3).

FLOATING STRUCTURES

The main experimental work was carried out in a two-dimensional tank in which the basic column shape was kept static for various geometric arrangements. However, in reality, the basic column contained in a floating structure would have to exist with various degrees of freedom in a deep water situation. In order to develop a design it was necessary to examine the interaction of its motion with the efficiencies and behaviour of the water columns.

One of the fundamental problems of a floating wave energy structure is that, unlike ships or offshore structures which are hydrodynamically streamlined, wave energy structures have, by definition, to interact with and absorb the incident wave energy. It is likely therefore that very large forces associated with this absorption would be experienced and the basic design problem to be resolved was how best to react these forces.

There were three possible options available:

1 Transmit the forces to the seabed. This was likely to be practicable only with a shallow water device as it is undesirable to transmit large forces through mooring systems.

2 Balance the positive and negative wave forces between adjacent waves either along the wave or at right angles across the wave crest. This required very long structures to be created in order to span large distances and the cost effectiveness was then questionable. Extending the device along the waves was of course possible and is favoured by at least one device. However, we believe this approach does pose practical and engineering difficulties.

3 Resist the forces locally by utilizing the inertia of the structure and that of the water in its vicinity (Fig. 4). The 'added mass' would thus be the major means of resisting the forces likely to be generated.

It was the third approach which was adopted by NEL and during the course of the hydrodynamic investigation many model shapes were tried and investigated in the wave tank.

Figure 5 shows a selection of these. The first, Fig. 5(a), is particularly interesting since this shows an early asymmetric model of the wave spanning type where the back reflector is in the horizontal plane. This has the effect of preventing wave transmission like a vertical deflector. However the best efficiency which could be achieved with this device was well below 50 per cent for a floating two-dimensional model. It is interesting to note that CEGB Marchwood Engineering Laboratories have decided to study this model in a long spine three-dimensional form whereby they claim much better performance due to the restriction of hydrodynamic response achieved by the third dimension. The second shape, Fig. 5(b), performed slightly better than the first although still only achieving peak efficiencies of less than 50 per cent. One of the major difficulties is that when a floating body is induced to move it has the tendency to generate waves which would radiate from it. The fourth model, Fig. 5(d), was the first in which the effect of wave cancellation was observed. The tendency to radiate waves had been greatly reduced and it was clearly observed that the incident wave was being completely absorbed by the device with insignificant wave radiation from the device itself.

The fifth shape, Fig. 5(e), was a further optimization whereby the overall volume was reduced, with little detrimental effect to the device performance. The option to close off the back section, shown dotted, was examined as a possibly desirable feature from a full scale constructional aspect. A two-dimensional model of this device is shown in Fig. 6.

The third model, Fig. 5(c), was the one selected as a shape which would be more readily constructed in reinforced concrete.

POWER EXTRACTION

Throughout the period when the hyrodynamic shape was being developed, it was important to develop in parallel an efficient and reliable method of extracting energy from the column. The simplest one envisaged was to use the air displaced by the water in the column to drive a machine. The characteristics of the air flow out of the column are a high velocity with a low inertia. The nature of the application calls for a high degree of reliability and robustness in the machine. In order to preserve the high conversion efficiencies of the wave to air phase it was important to ensure that the characteristics of the machine matched as closely as possible those of the column, otherwise excessive damping would have been applied to the column preventing it from operating efficiently.

A Francis turbine was selected as giving the characteristics most closely matching those of the column. Although Francis turbines are normally used in hydro-electric power stations operated by water, the machine can operate equally well using air as the fluid. The Francis turbine is a very efficient machine and its compact design makes it a robust and reliable device (Fig. 7).

Associated with the air inflow to the turbine it was necessary to conceive a ducting and rectifying arrangement whereby air could be converted from a reciprocating flow to a uni-directional flow through the turbine. A four-valve rectification system was conceived (Fig. 8) to achieve this uniform direction of flow.

A programme of work was carried out in parallel with the hydrodynamic development which examined the characteristics of a radial inflow Francis turbine at model scale together with a rectifying valve arrangement. The experimental work

(Fig. 9) has shown that this system operates satisfactorily in a pulsating airflow regime and it has been shown that mean annual efficiencies of the order of 80 per cent can be achieved from these turbine systems.

FULL-SCALE DESIGNS

At this stage the services of a consulting engineering organization experienced in civil and offshore works were required and Roxburgh and Partners were selected as members of the NEL team. The combination of the hydrodynamic work with the turbine development and with other ancillary studies examining mooring and other force regimes led to full-scale designs being produced by the team in 1978 for a 100 MW power station. Two designs were in fact carried out: one of steel construction to be built by conventional shipyard techniques and the second of reinforced concrete constructed in a manner similar to that used for gravity offshore structures.

Reference Design in Steel

The cross-sectional shape adopted for the steel design was that which gave the best overall efficiency in the tank test. The reference design (Fig. 10) could readily be constructed in a conventional shipyard. The overall dimensions of the steel design were 121.5 m long by 35 m wide by 33 m high. Each unit consisted of a bank of 6 modules each containing a column. The construction was designed to take place on a shipyard slipway although an alternative configuration for construction in a dry dock was also prepared. The specifications used were those which are current practice in tanker construction and each unit had a floating steelweight of around 12 000 tonnes.

Reference Design in Reinforced Concrete

The construction in concrete required that the most efficient hydrodynamic shape be modified to enable construction to be reasonably practicable. The shape which was used (Fig. 11) was rectangular, 35 m wide with a draft of 25 m in still water conditions, and consisted of six water columns each 12 m by 18 m cross section. The overall size of each unit was 116 m long by 35 m wide by 35 m high. It was proposed that the structure would be constructed using the dry dock technique as for large offshore production platforms where the base tray is cast in the dock, then the dock flooded, the tray floated out and moored and the structure completed by slip forming while afloat.

Offshore Construction

The 100 MW output power station designed was intended to operate off the west coast of Britain in an approximately north/south line and the 25 units needed to produce the power would occupy a sea distance of 13.5 km. The structures would be moored in an end-to-end configuration with approximately 400 m clear between each to allow the necessary compliance in the mooring systems.

The structures would be moored using a tensioned hawser system with conventional high-holding-power drag anchors and the addition of clump weights to improve the uplift resistance. The proposed mooring system was made up mainly of man-made fibre ropes using their inherent strain energy storing characteristics in preference to wire or chain, thereby providing sufficient elasticity to eliminate snatch forces.

These structures were intended to be intermittently manned and the necessary accommodation and safety equipment was provided on board each unit.

The object of carrying out the design studies was to examine the feasibility of such a design and to produce an estimate for the cost of generating electricity from wave energy.

The result of the study of the floating 1978 reference design indicated that the costs of producing electricity by these designs were high and likely to be of the order of three to five times greater than was attractive as an alternative form of energy.

FIXED STRUCTURES

Oscillating water columns fixed to the seabed were considered early in the programme but were initally discarded because the incident wave energy would be greatly attenuated in shallow water and therefore fixed columns seemed unlikely to offer a cost effective power generation system. Examination of the cost centres of the floating designs showed that, over the life of the structure, approximately 30 per cent of the capital repayment and maintenance costs related to the moorings. This led to the suggestion that a study of a bottom-standing device might show worthwhile cost savings.

A fixed structure in shallower water would have the following advantages:

- Less space between devices
- Lower survival wave heights
- Higher energy conversion efficiency
- Easier maintenance
- No flexible power cable
- Closer proximity to shore
- Higher load factor

The main disadvantages might be:

- Lower incident wave energy
- Interference from seaweed
- Installation difficulties

Space Between Devices

Since the devices are fixed to the seabed they can be placed in continuous lines, thereby absorbing 100 per cent of approaching wave energy in any particular location. This is in contrast to the floating devices which due to the necessity for fully compliant moorings could only present a 20 to 30 per cent absorption front to the waves.

Lower Survival Wave Heights

Depending on the characteristics of the chosen site the maximum wave which can occur is water depth limited and usually of a height less than that in deep water. In the case studied, the site depth was chosen as 18 m and the corresponding 50-year design wave was assessed as having a maximum height of 15 m.

Higher Energy Conversion Efficiency

With a fixed oscillating water column it becomes possible to absorbe the energy from both the short wind waves andthe long swell (Fig. 12). In contrast the floating oscillating water column tends to extract energy only from the shorter waves. Thus a much larger proportion of the incident wave energy is available for conversion to power.

Easier Maintenance

Any floating structure designed to extract wave energy is likely to be constantly moving. A fixed structure however, makes maintenance of itself and its onboard plant much easier, and by its fixity, stresses the plant less severely, thereby reducing wear and tear and reducing the maintenance requirements.

No Flexible Power Cables

Power transmission from floating devices using flexible cables is likely to be very expensive in initial capital cost and subject to breakdowns due to flexing o external interference. Indeed, suitable power cables have yet to be developed by industry. A fixed bottom-standing device eliminates the need for flexible power cables and the problem is reduced to one of maintaining an existing type of fixed cable such as is in common use on many underwater power links.

Closer Proximity to Shore

By siting the device in water depths around 18 m the distance offshore is reduced to about 1 to 5 km from landfall dependent on local conditions. This gives a shorter transport distance for men and materials and creates a more sheltered environment in the lee of the structure for operation of maintenance vessels. It also reduces greatly the lengths of underwater cable required to land the power.

Higher Load Factor

Moving the device inshore into a less extreme wave climate and mounting it on the bottom will result in an improved load factor. The extreme waves found in deep water (greater than 40 m depth) can no longer occur at the device since the wave height is now water depth limited to about 15 m and the general wave front is likely to be refracted by the bottom effects making it more nearly parallel to th line of devices. This is expected to result in a greater proportion of usable wave energy being available to the device.

Lower Incident Wave Energy

While a lower wave incident energy might appear as a disadvantage, the much highe conversion efficiency that can be obtained from a fixed, as opposed to a floating structure together with the possibility that the incident energy is distributed i a regime which contains less unusable peaks, could be a positive advantage.

Interference from Seaweed

The heavy forest of kelp which is found off the west of the Hebrides was feared t be a problem in reducing incident power and obstructing the flow within the oscil lating water columns. A study commissioned from the Scottish Marine Biological Association showed that the bulk of the kelp forest (identified as being Laminari hyperborea) occurred inshore of the 18 m depth selected for the device and that neither the growing kelp nor the seasonally cast fronds or stalks were likely to pose any serious problems in respect of diminution of power output or of maintenance. The report further showed that other marine fouling species were

unlikely to prove of significance from an operating or maintenance point of view.

Installation Difficulties

The emplacement of a structure of relatively modest self-weight which has a natural draft of the same order as the water depth in which it is to be founded, poses several problems. The structure must be given auxiliary buoyancy prior to emplacement, be rapidly set down on station and quickly ballasted to full stability thereafter.

The use of a purpose designed catamaran barge is the currently preferred method of installation. This also provides the working platform for rock anchoring the structure to the seabed. Its expense can only be justified in a very large development. Further development of emplacement proposals forms a major part of a continuing study.

SAME AS 1981 PAPER

APPLICATIONS FOR FIXED BREAKWATER WAVE ENERGY STATIONS IN REMOTE COMMUNITIES

There is no doubt that Britain holds a substantial lead in wave energy technology relative to the rest of the world.

Most of the work carried out in the UK has, however, been directed at investigating the possibility of obtaining, within a reasonable time-scale a substantial proportion of the UK energy requirements and Fig. 13 shows the NEL breakwater type wave piston designed for that purpose.

The development of wave energy may not proceed directly to this objective as, in common with most other engineering developments, a step-by-step approach is likely to prove more practical. There are many locations in other parts of the world with a less severe wave climate than that existing in north-west Britain. These locations could be served by single or multiple wave energy stations. For example, the Pacific, Atlantic and Indian Oceans, particularly in the southern hemisphere, have many coastal zones facing a long fetch. In these locations are climates which are capable of providing consistent and readily convertible wave energy without the considerable survival problems that apply in more temperate zones, and unlike UK do not have indigenous reserves of hydrocarbon fuels.

From the commercial viewpoint, the power authorities in those locations are unlikely to be readily convinced that they should build wave energy stations or buy British wave power technology if the UK did not mount a demonstration project for one of its own remote communities.

In seeking a location for a demonstration project, it would be preferable that it should not be connected to the national grid but be served by a local grid supplied by diesel generation. A compatible supply, provided by the wave energy station, could then demonstrate a direct fuel saving, whilst at the same time it could rely on the original supply as a back-up for periods of calm weather. Various UK locations have been considered, in particular island communities, that appear to meet the criteria desirable for a demonstration to be provided.

PRELIMINARY STUDY OF A SITE IN TROPICAL WATERS

The problems of constructing a single wave energy station (less than one megawatt say) are substantially different from those of a major installation of many gigawatts.

In the case of a fixed shallow water device, the construction of a small single station will rely very much on standard maritime civil engineering techniques.

This is in contrast to the mass production and sophisticated installation techniques upon which the economics of a major scheme depend.

A preliminary exercise for an island in the Southern Pacific Ocean, (Fig. 14) utilizes a sheet-piled coffer dam of elliptical plan shape.

The wave piston chamber is formed of in situ concrete within the coffer dam which also provides the housing for the turbo-generating plant.

Immediately prior to start-up, an opening is made in the front of the coffer dam so that wave power can be abstracted from the sea into the device.

A further stage in the development of the device illustrated will be a series of tank tests so that the output can be equated against costs and the economic viability confirmed.

CONCLUSION

It is considered that a wave-power station for a remote community of the order of power of 1-5 MW would have a significant place in a 'step-by-step' approach to the exploitation of the major wave energy resource, both for the UK and other parts of the world. Indeed it could provide the breakthrough needed to allow this infinite, inexhaustable source of power to be harnessed for mankind.

ACKNOWLEDGEMENTS

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LIST OF FIGURES

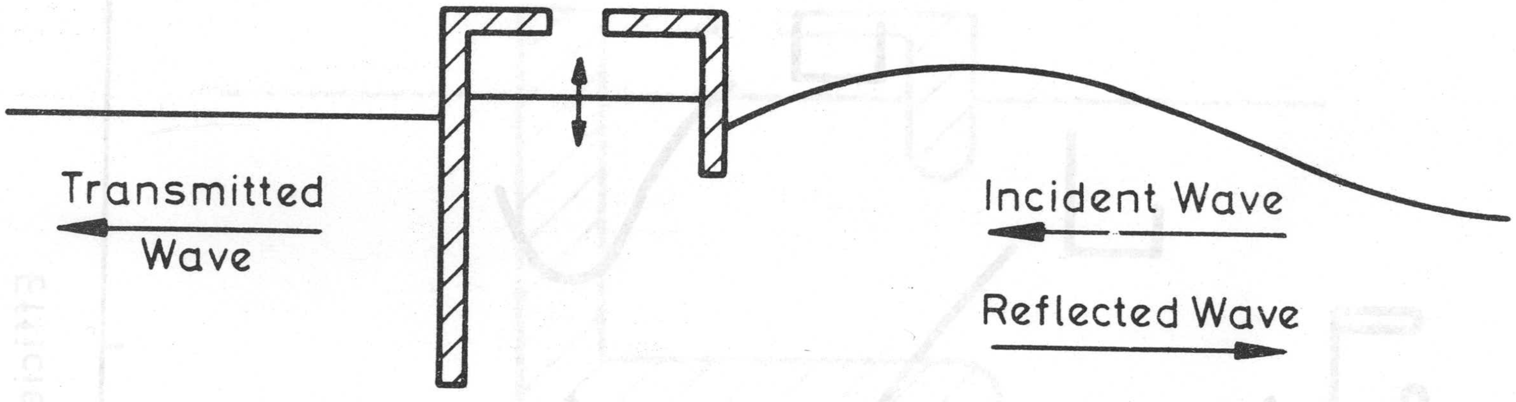

FIG1 TWO- DIMENSIONAL OSCILLATING WATER COLUMN

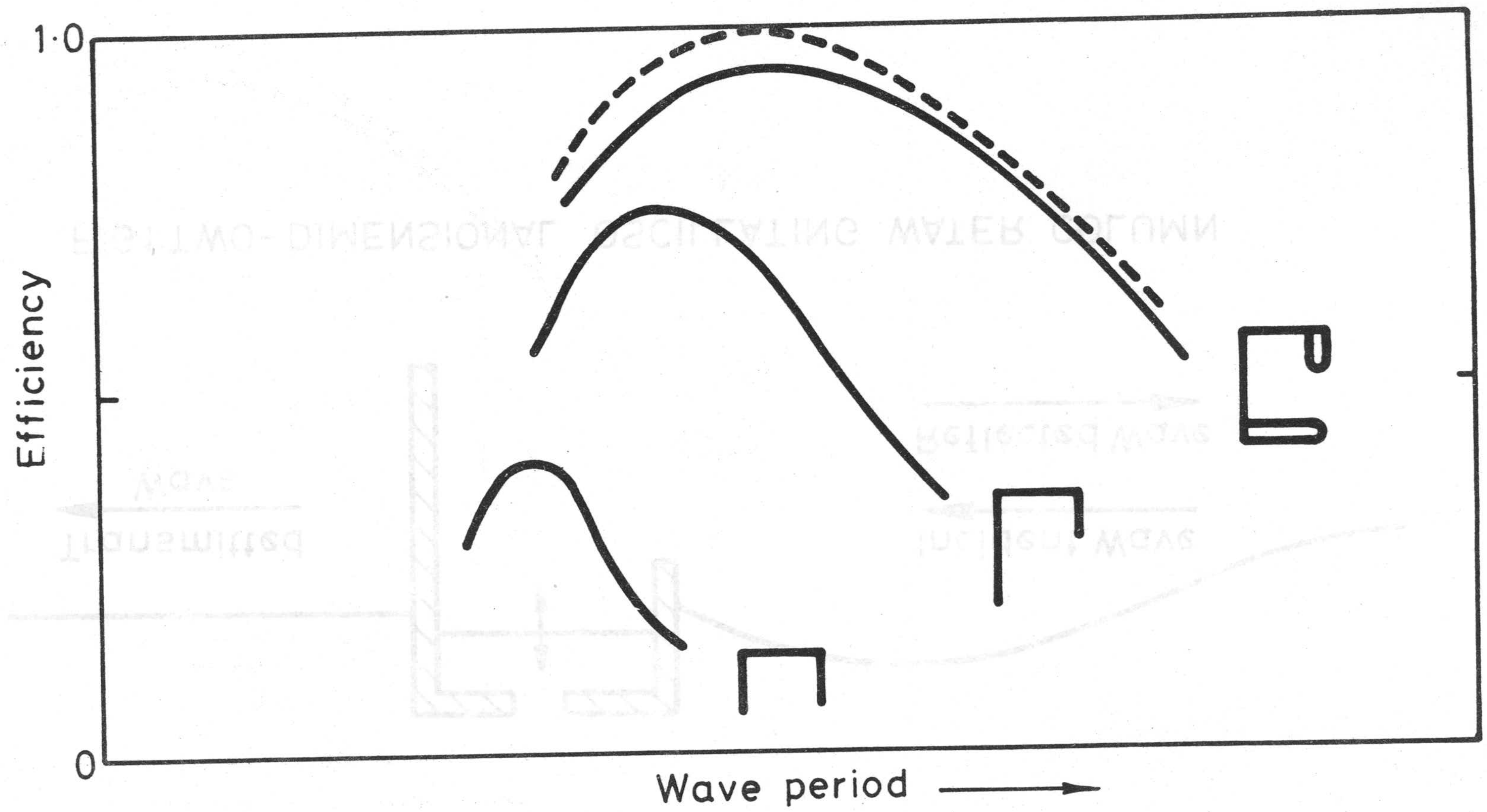

FIG 2 EFFICIENCY AND COLUMN SHAPE

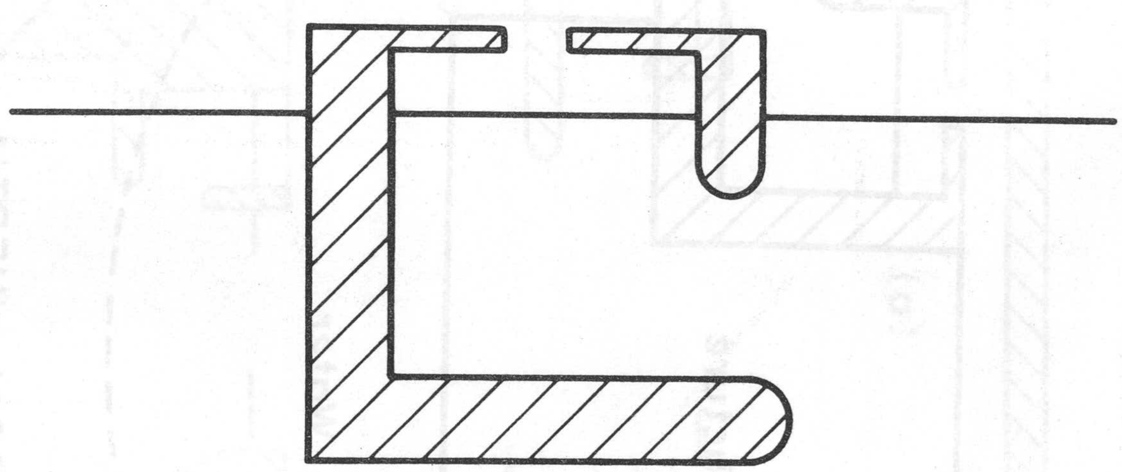

FIG 3 PREFERRED COLUMN PROPORTIONS

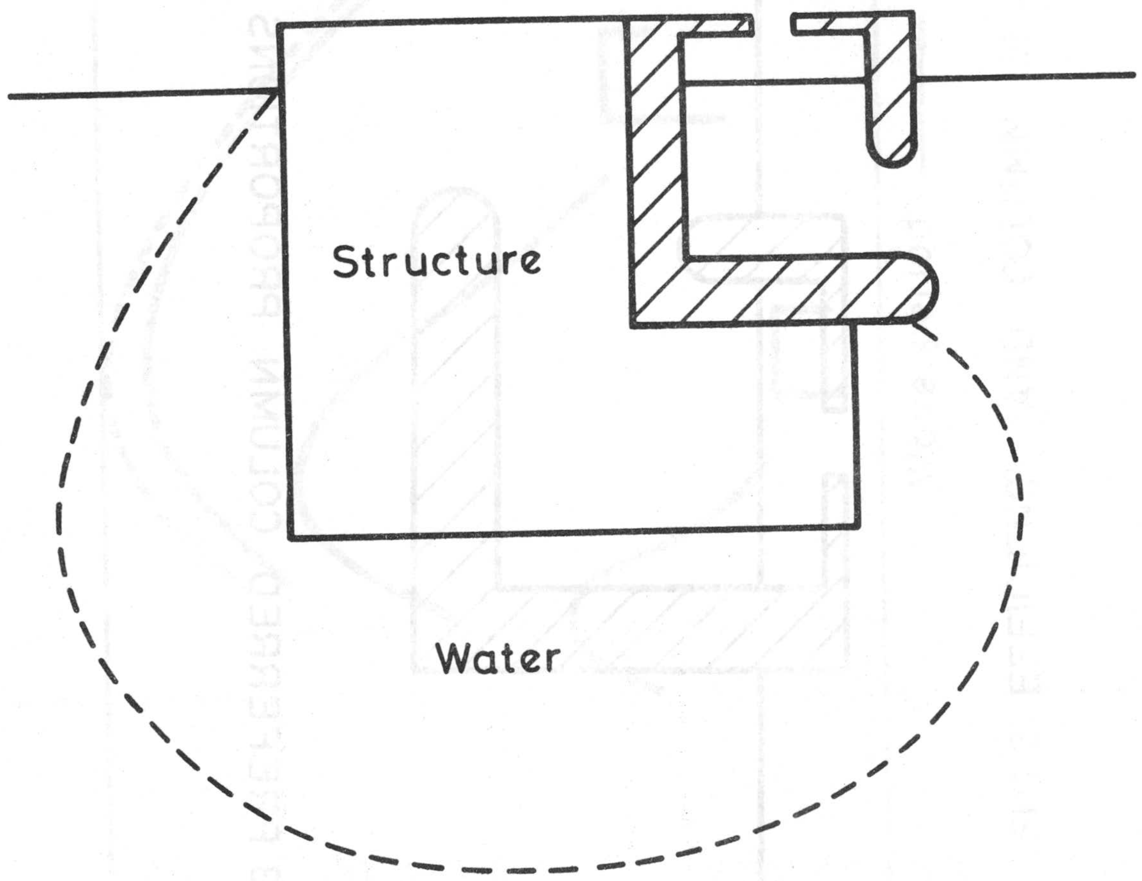

FIG 4 LOCAL INERTIA

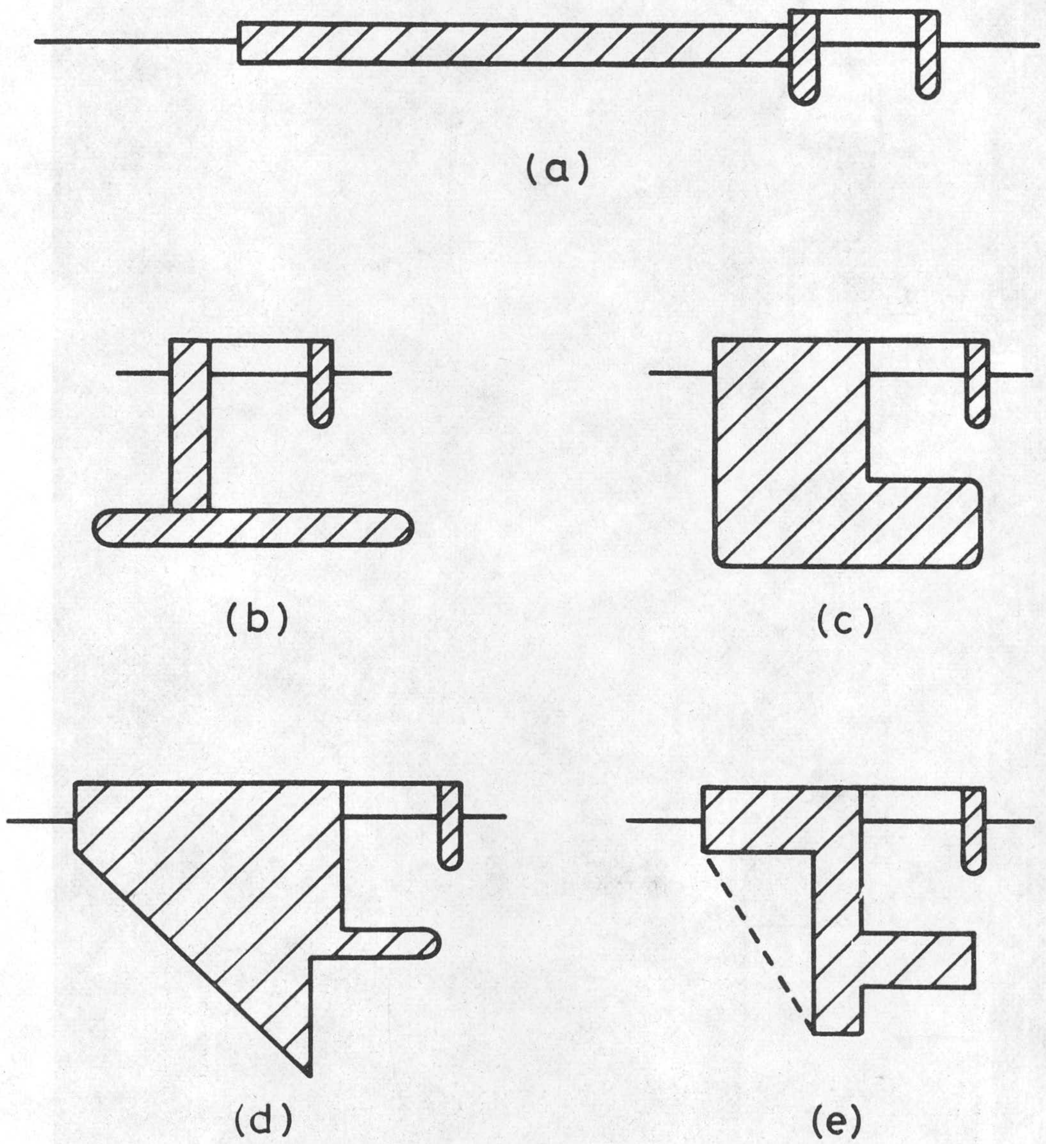

FIG 5 SOME OF THE SHAPES TESTED

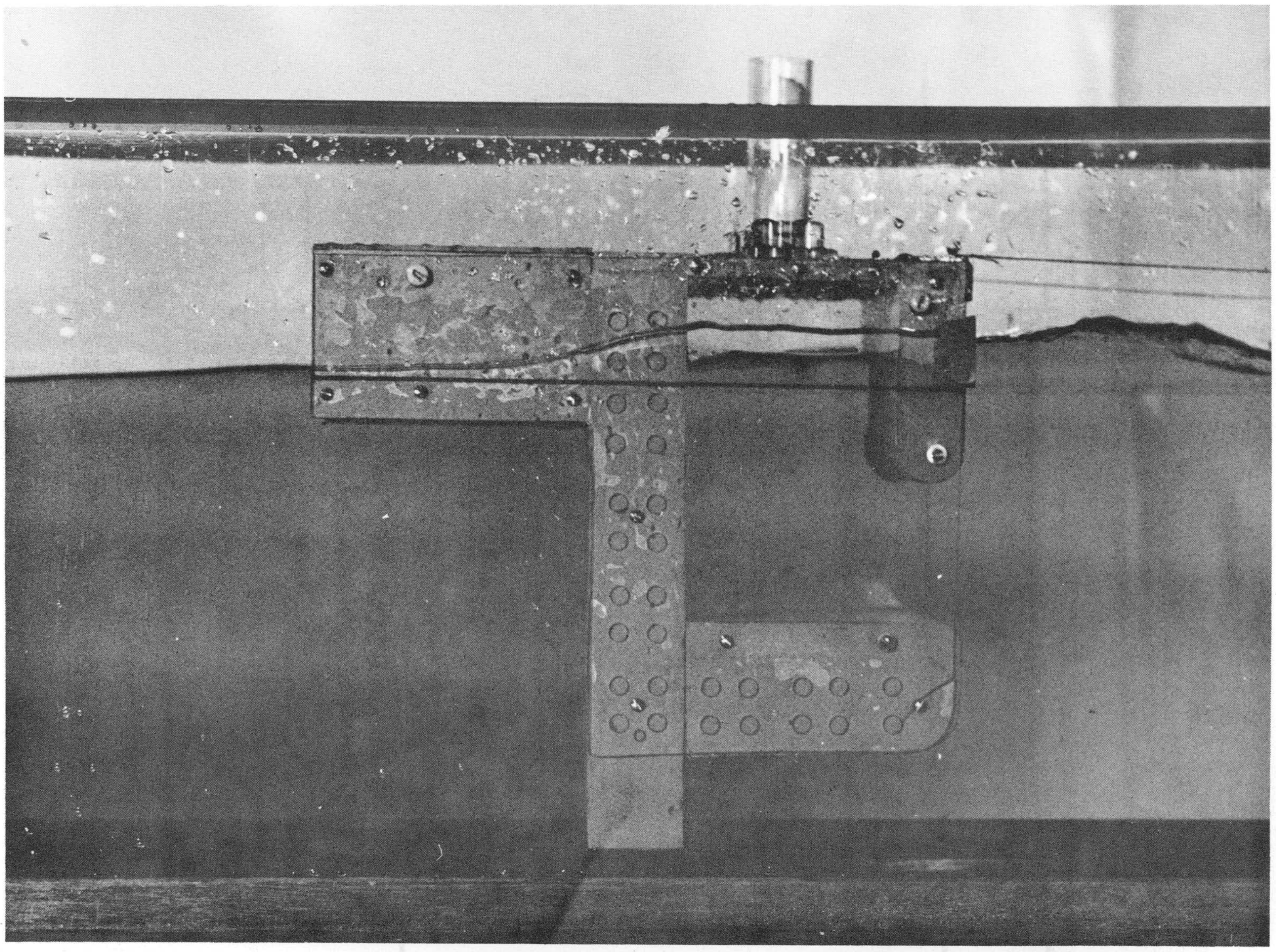

FIG 6 TWO - DIMENSIONAL MODEL OF PREFERRED SHAPE IN TEST TANK

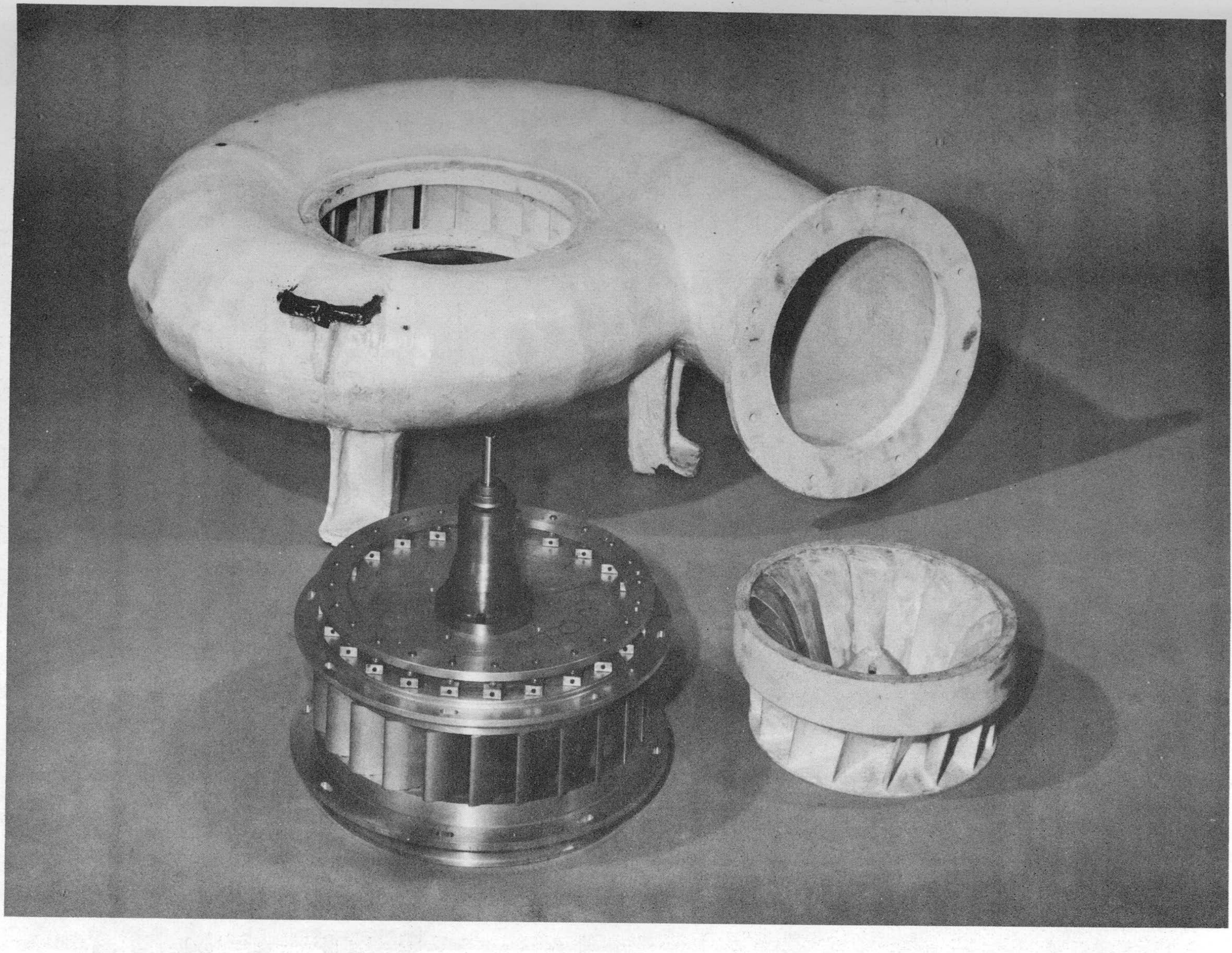

FIG 7 FRANCIS TURBINE COMPONENTS

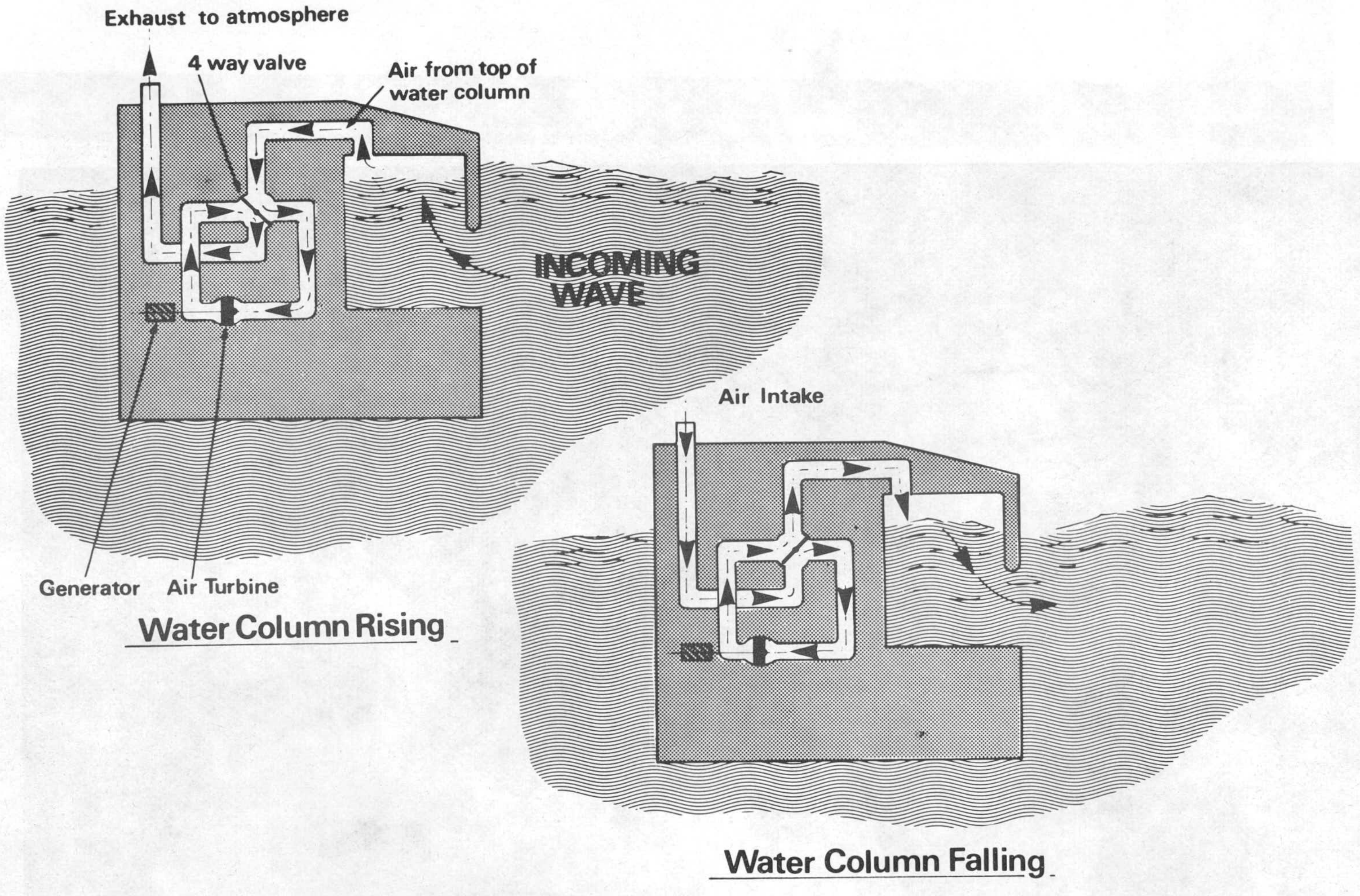

FIG 8 SCHEMATIC OPERATION OF NEL OSCILLATING WATER COLUMN

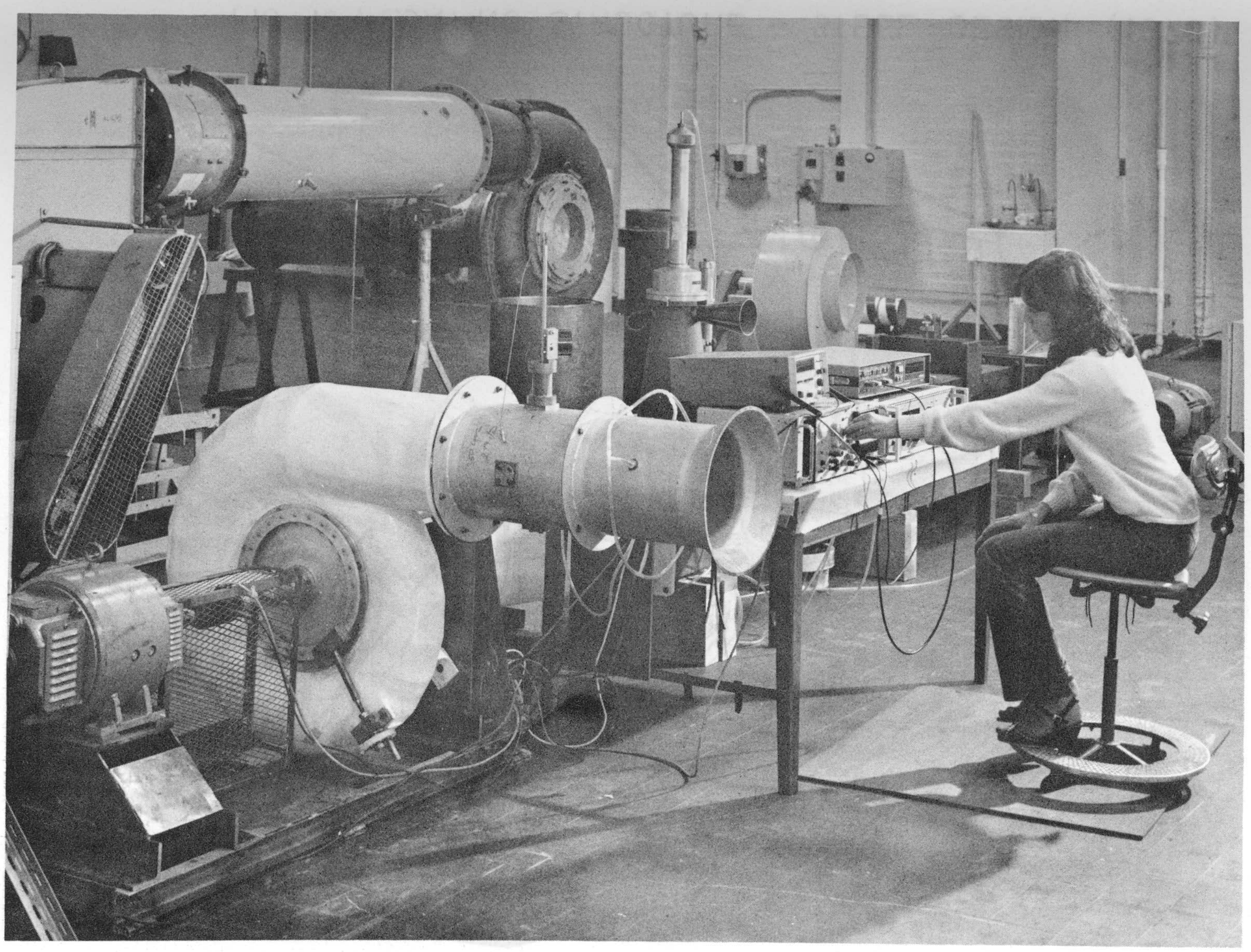

FIG 9 TURBINE TEST RIG

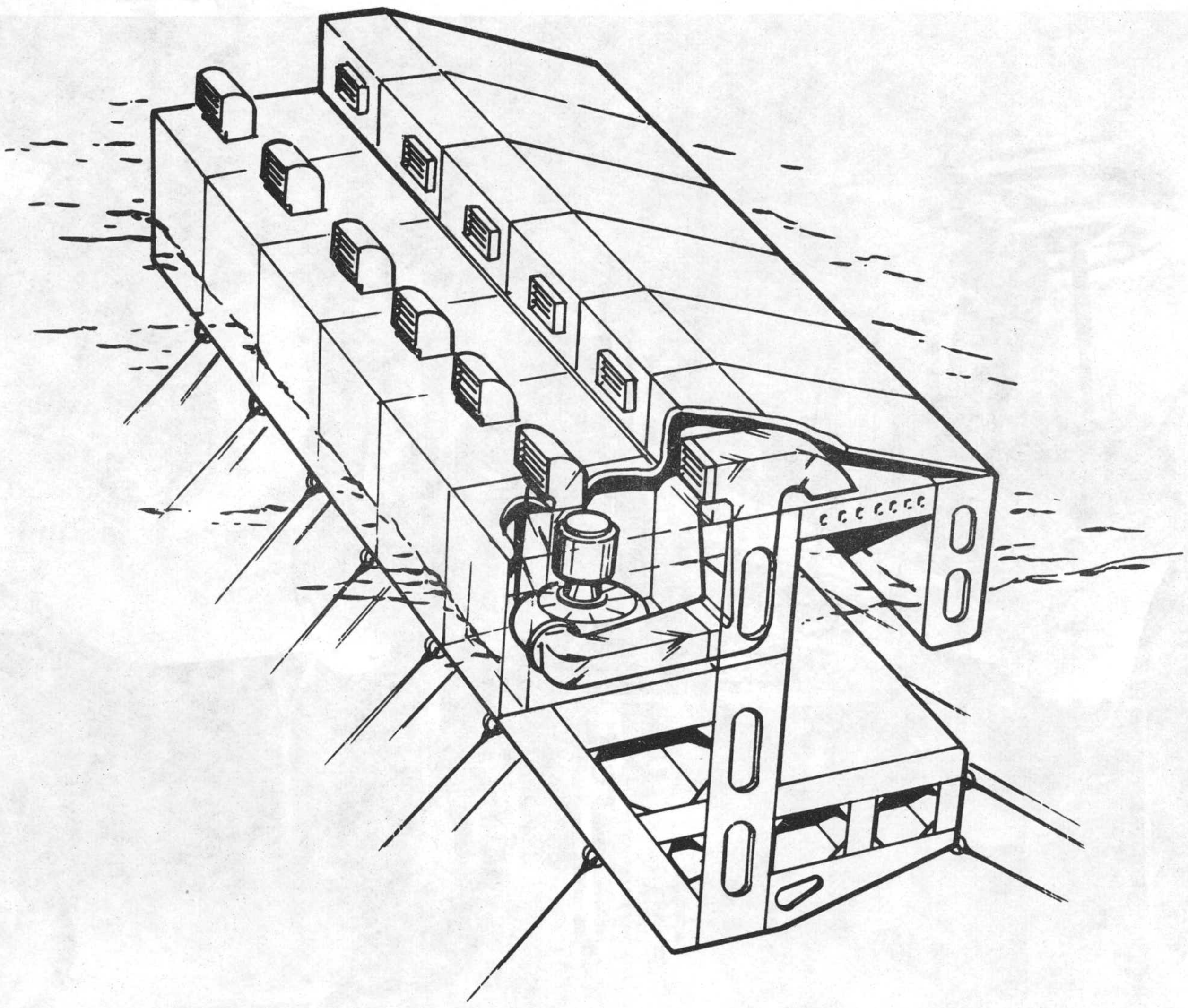

FIG 10 FLOATING STRUCTURE – STEEL DESIGN (1978)

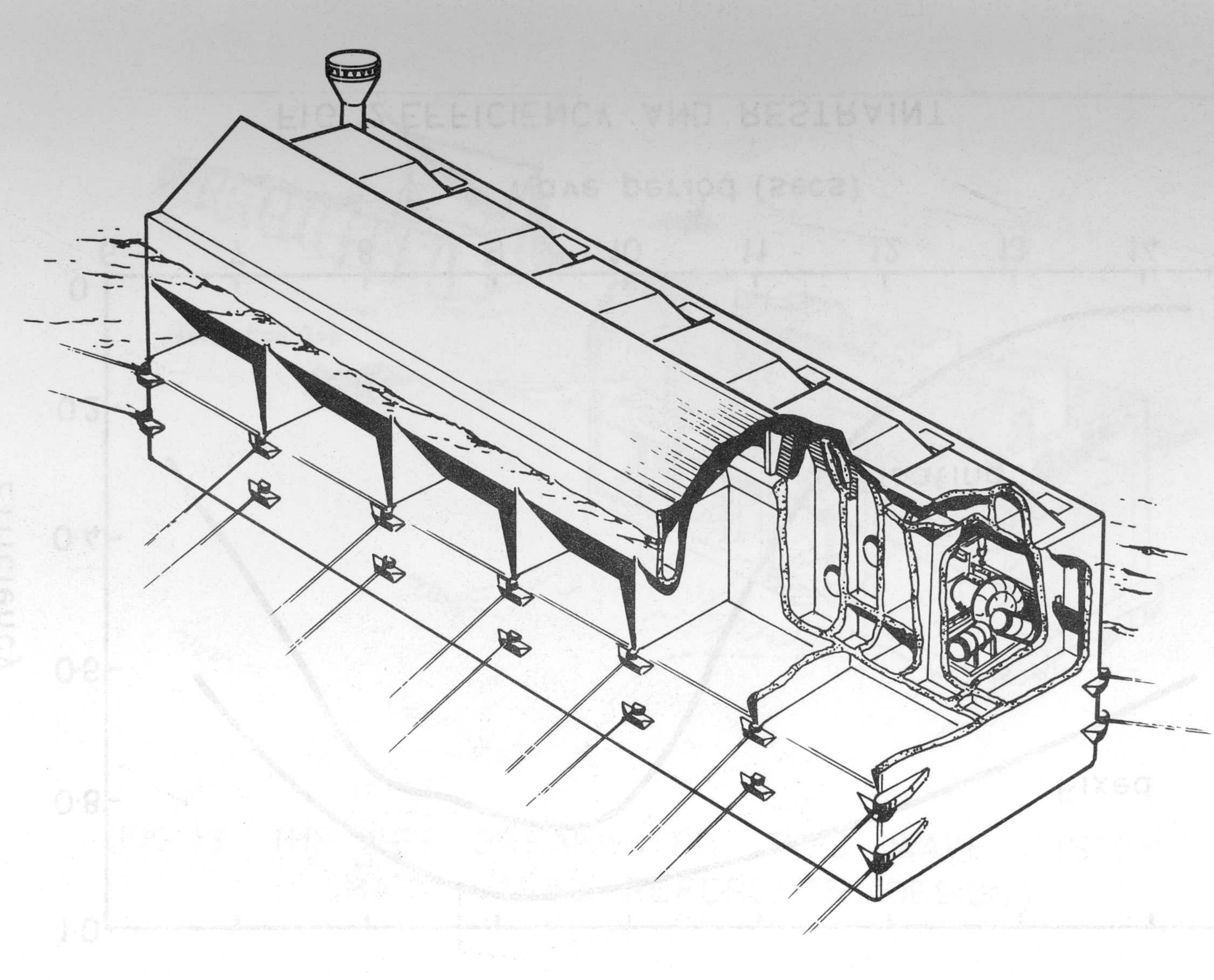

FIG 11 FLOATING STRUCTURE – CONCRETE DESIGN (1978)

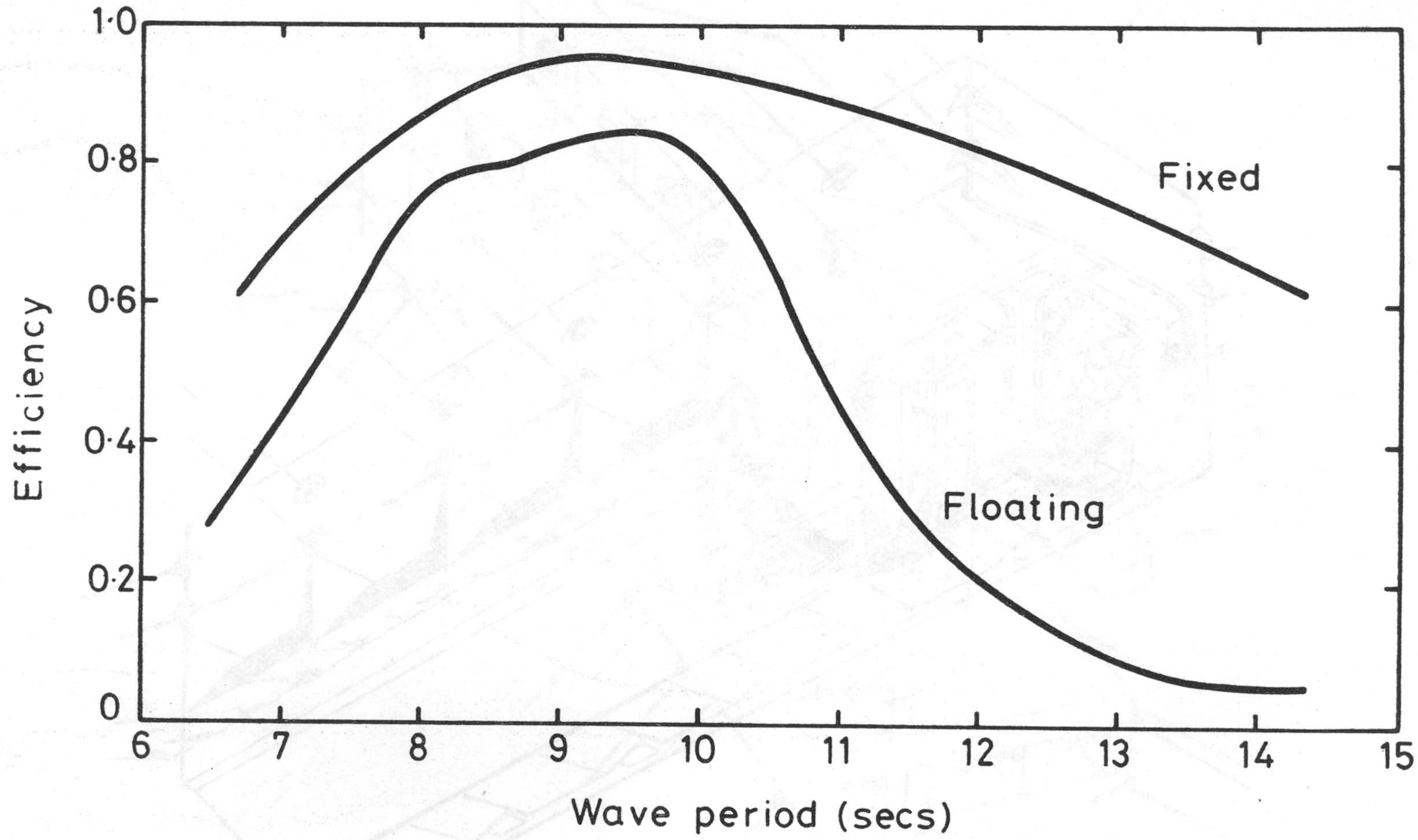

FIG 12 EFFICIENCY AND RESTRAINT

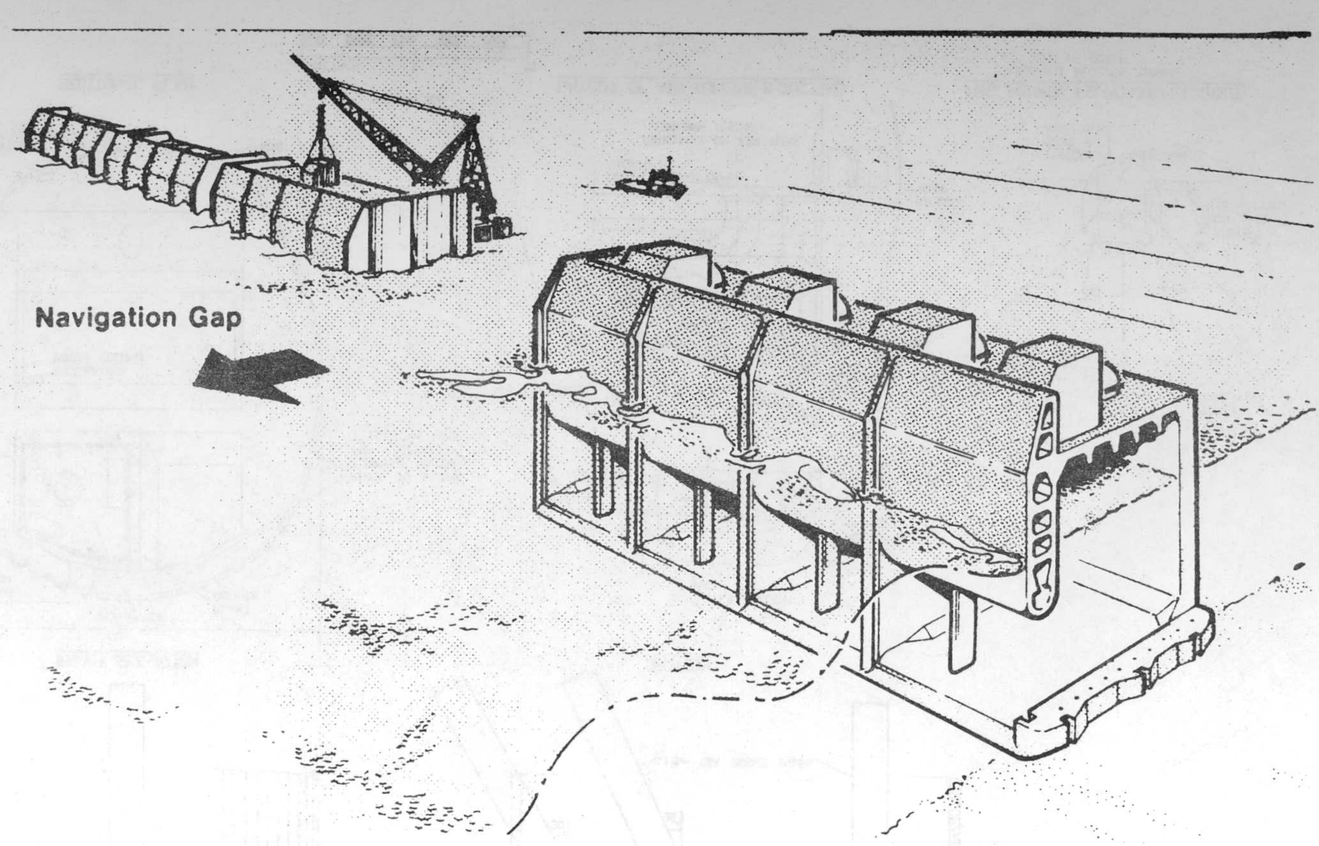

FIG 13 THE NEL BREAKWATER TYPE WAVE PISTON
(MARCH 1980 REFERENCE DESIGN)

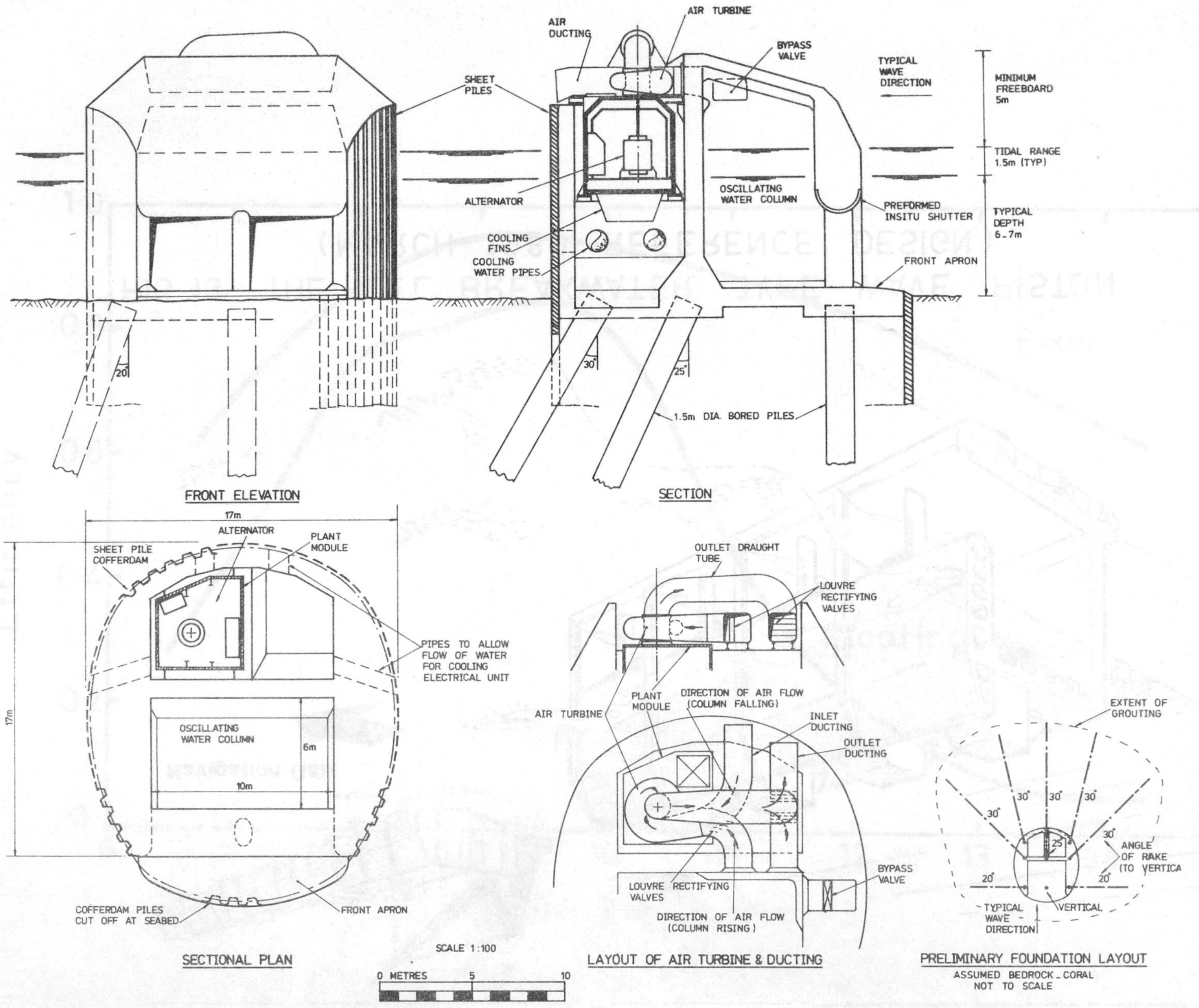

FIG 14 PRELIMINARY SKETCH OF SMALL WAVE-POWER STATION